

Electrostatic Appliqué for Spacecraft Temperature Control

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Abstract. The electrostatically controlled radiator (ESR) uses electrostatic hold-down of a high emissivity composite film to control spacecraft skin temperature. It functions as a thermal switch and changes the mode of heat transfer between the spacecraft skin and the radiator film from conduction to radiation and has demonstrated large changes in apparent emissivity. The present device operates at high DC voltages and is designed with a rigid backing. An improved version, termed a micro-ESR, is being fabricated as an appliqué. Since the size has been reduced, much lower operating voltages are possible. In addition, the system is conformal, allowing it to be applied to complex surfaces. This paper discusses the results from vacuum testing of the existing ESR devices. It also describes the process to form the appliqué.

THEORY OF OPERATION

The approach is based on the use of a cover film that is attracted to the skin of the spacecraft via electrostatic forces. The cover film is a flexible, compliant film and can establish good thermal contact with application of the voltage. When attracted, the emitting surface of the cover is at the skin temperature. Since the outer surface of this cover is fabricated with a high emissivity coating, the result is that the system radiates with a high emissivity (~ 1). Alternately, in the off state when the film is released, it is moved slightly away from the skin. The only thermal interaction between the skin and the cover film is via radiation. In equilibrium, the total energy radiated by the system (outer cover) is limited to that radiated from the skin, which can be fabricated with a low emissivity. The emissivity of the outer cover doesn't change, however its temperature drops and the result is a drop in the radiated energy. We treat this as an effective emissivity. It is potentially possible to switch the energy radiated from an $\epsilon \sim 1$ to $\epsilon < .05$. In addition, this approach has minimal requirements on the front surface, so conventional white paints can be used to control solar absorbance. A schematic of device operation is shown in Figure 1.

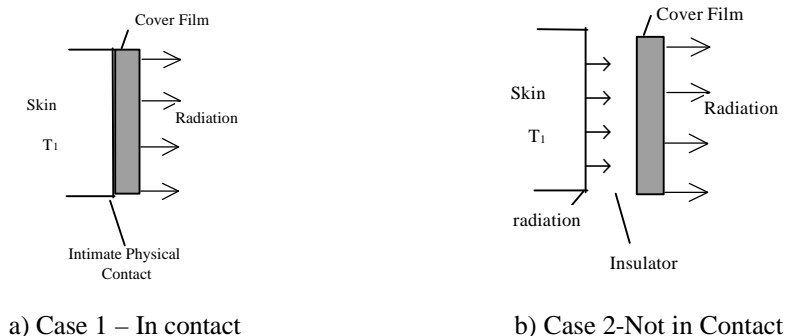


FIGURE 1. ESR Theory of Operation.

A sketch of the current ESR device is shown in Figure 2. It consists of a composite cover film anchored to the skin of the spacecraft at the edges. This cover film consists of a high dielectric constant insulator with a high dielectric strength and coated with an electrically conductive layer. Since there are few other restrictions on this cover, this combination can be achieved with an appropriate paint or, for better performance, a multilayer thin film designed for very low visible absorbance. The top surface of the skin should have a very low emissivity, i.e. sputtered gold. A picture of an operational ESR is shown in Figure 3.

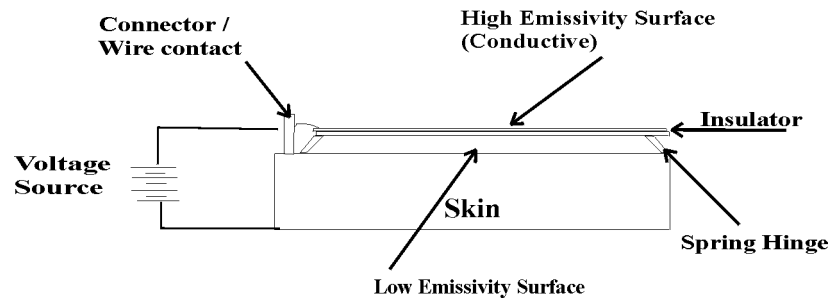


FIGURE 2. ESR Construction.

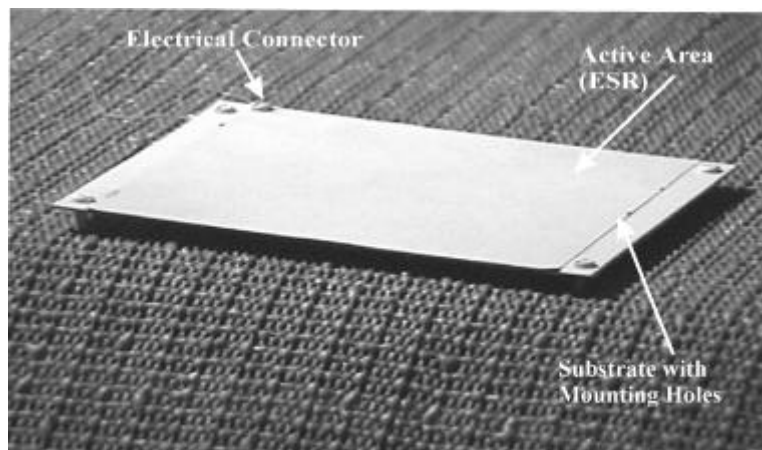


FIGURE 3. ESR Test Assembly Including Mounting Brackets and Electrical Connectors.

With this particular design, the outer film is at a high voltage, which is required to operate the device. The design shown in Figure 4, with a small change in electrical characteristics, avoids this problem. This design adds a second “capacitive” layer. The outer skin is at ground potential, as is the substrate. The voltage is applied to the inner layer. This design shields the DC fields and eliminates any potential hazard if the cover of the ESR is shorted. The only electrical change is an increase (approximately by 50%) in the capacitance, with the consequent small increase in power loss when switching.

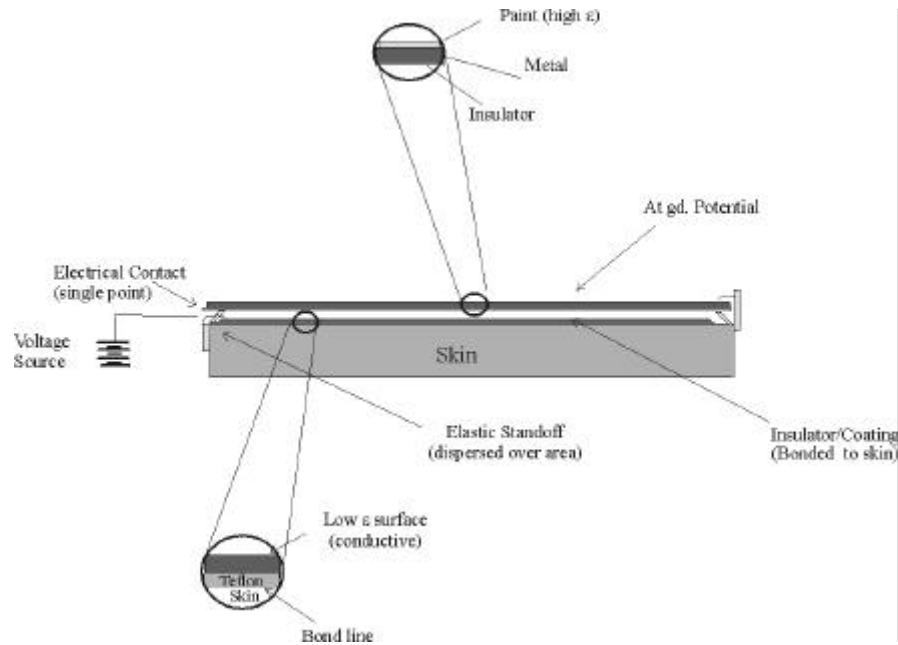


FIGURE 4. Shielded ESR Design with Outer Layer at Ground Potential.

TESTING

Since the method of heat transfer to the environment is radiation, this device will only operate in space-like conditions, i.e. low pressure to minimize any convection into cold background. A system to simulate these conditions is shown in Figure 5. The sample is placed on a thermal control plate and the heat loss is measured either by measuring the temperature change with time, or the power required to maintain temperature and is basically a calorimetric approach. Although the heat loss with switching can give an accurate measure of a change of emissivity, stray losses (radiation from the back, un-switched areas, stray wires, leads, etc.), requires a calibrated sample to obtain emissivity values. Our calibration used a sputtered gold film as the “zero” and a black paint for the high value ($\epsilon \sim .9$).

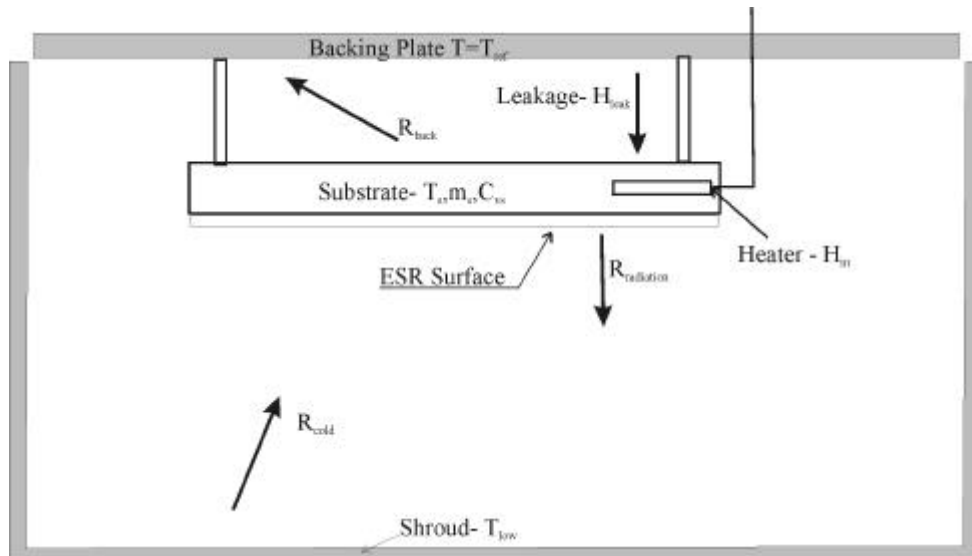


FIGURE 5. Sketch of Emissivity Measurement System.

Figure 6 shows measured results for a sample consisting of one of the standard ESR's. For this measurement, the voltage was applied while the sample was warm and showed basically the best performance that can be obtained, with a measured $\Delta\epsilon$ of .74. Unfortunately, when this sample was left in the "off" state, the film took a "set" and the "on" values decreased drastically. This problem likely can be resolved by careful design both of the "hinge" and the material selection (this device used mylar for the cover film).

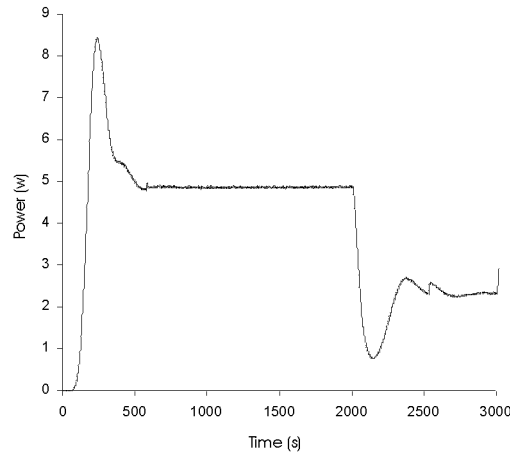


FIGURE 6. Power Input Measurements of Thin Metallized ESR. $\Delta\epsilon = .74$.

Figure 7 shows the results obtained on a more reproducible and controllable device, with some sacrifice in emissivity. The film surface area was 9.2 cm x 9 cm and the radiation switched was 21.87 mW/cm². This corresponds to a $\Delta\epsilon$ of 0.512 (high ϵ of .9 and a low ϵ of .388). This particular sample was manufactured with a more thermally conductive top electrode. This configuration likely increased the lateral heat flow in the "off" state and limited the low temperature in this off-state. The more modest $\Delta\epsilon$ which results also has a much lower temperature excursion. The calculated temperature for this cover film for a low ϵ of .388 is 269K. There is minimal stress on the cover film in this "off" state and careful design of the hinge mechanism should allow reliable operation at much lower temperatures with the resulting larger control range for the radiation from the surface.

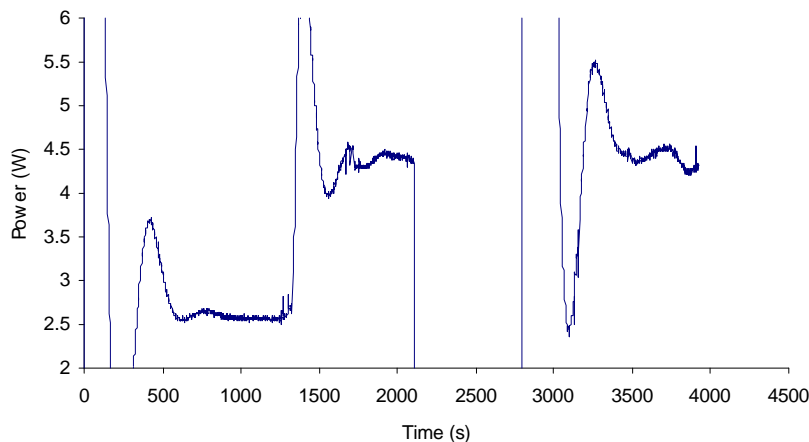


FIGURE 7. Power input measurements of ESR. Area was 92x90 mm. and "on" power corresponds to 39.06 mW/cm² and the off state was 17.19 mW/cm². This corresponds to a $\Delta\epsilon$ of 0.512. (high ϵ of .9 and a low ϵ of .388. 1/8" Al Pyralux LF 7012 [Cu 0.5 oz/ft² + 0.5 mil adhesive + 0.5 mil Kapton])

FLEXIBLE APPLIQUE

The ESR requires a controlled base, a substrate with a low emissivity coating which is reasonably flat so the ESR film can make a good thermal contact. In the above examples, this was assumed to be the outer skin of the spacecraft. However, for most applications, it would be more desirable to apply the ESR as a conformal film over the outer skin. As long as the ESR base is in good thermal contact with the skin, defined as being at the same temperature as the skin, this should present no problems in performance.

In particular, it is possible to fabricate the ESR as an appliqué which can simply be attached to the outer skin of the spacecraft. Since the heat flows are small, it is relatively easy to have this proposed ESR appliqué be electrically isolated but in good thermal contact with the skin.

This structure is shown in Figure 8. It consists of a flexible substrate, e.g. a thin film of a polyimide coated on both sides with a conductor. Using techniques similar to MEM's fabrication but adapted for polymers; a small structure is manufactured, replacing the free-standing membrane, by an umbrella-like structure. Application of a voltage attracts this membrane to the base structure, which is at skin temperature, while releasing the voltage allows the membrane to "spring" back.

The advantage of this structure includes easy application by simply attaching it to the outer skin. Depending on the exact substrate material and geometry, it will be somewhat conformal. Since the total thickness is <100 microns, the device is light-weight (< 200 grams/sq. meter). In addition, electrostatic forces are highly dependent on geometry, with the forces increasing as the inverse of the square of the separation, so the device will operate at much lower voltages than the existing device. The expected operating voltage is below 10 volts.

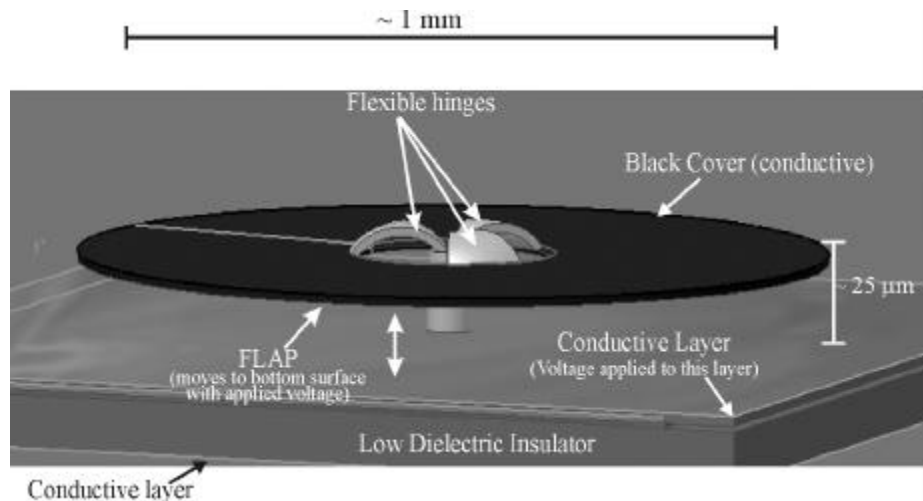


FIGURE 8. Electrostatically Controlled Radiator Appliqué.

APPLIQUE DESIGN

Since the sizes of the appliqué are quite different from the existing ESR, preliminary modeling is needed to estimate the performance range. The major concern is with the "off" or low emissivity state, where heat leaks from the base will limit the value for the low emissivity. There are two possible sources for heat leaks. One is the direct heat flow across the gap via any residual gas present and the second is via the mounting/contact points to the membrane itself.

The first heat leak is not a problem under normal operation. The ESR is designed for spacecrafts, where the pressures are low and the dimensions of the system are small compared to the mean free path. This condition is referred to as a rarified gas condition. In rarefied gases, the molecules do not undergo any collision and the molecules leaving one surface travel freely until they hit the other surface.

The amount of heat transferred from the first surface at T_1 to a second surface, at T_2 , can be calculated by assuming an “effective temperature” of the two surfaces. The system is treated by assuming the gases are at equilibrium between the two surfaces and the pressure given by the particle density at a selected altitude while the temperature is given by the average of T_1 and T_2 . In this case, the flux from a surface is given by:

$$F = nv/4 \quad (1)$$

where F is the number of molecules leaving the surface per unit time, n is the molecular density and v is the average velocity. n can be approximated using the density of gas at the spacecraft’s altitude while v is the mean speed of the molecules at temperature T . This velocity, using the average temperature, is given by (Reif, 1965):

$$v = (8kT_g/\pi m)^{1/2}. \quad (2)$$

Thus, the heat transferred between the two surfaces will be given by (Chapman and Cowling, 1991):

$$Q = n/4 * (8kT_g/\pi m)^{1/2} (T_{\text{skin}} - T_{\text{esr}}) \quad (3)$$

O_2 has a species concentration of $\sim 10^{16}/m^3$ at 150 km (Balthazur). Using O_2 with molecular weight 32, $m = 32 \times 1.6605 \times 10^{-27}$ kg; $k = 1.3807 \times 10^{-23}$ J/K; and $T_g = 230$ K results in a heat transfer of:

$$Q = 1.11 \times 10^{-5} \text{ Watts/cm}^2. \quad (4)$$

This can be neglected compared to the radiation at 300 K, of about $41 \times 10^{-3} \text{ Watts/cm}^2$.

The second heat leak is via conduction through the various attachment points to the membrane cover film. This heat will locally increase the temperature of the cover film, dependent on the thermal constants of this film. This is a difficult system to model since the temperature must be calculated over the surface and the radiation varies with the 4th power of the temperature. For initial work, a finite element program was used to calculate the average amount of heat radiated for selected geometries and thermal conductivity values. A 2-D structure was used for the modeling and is shown in Figure 9. This model assumes a continuous contact at one end, so it is a pessimistic approach since something closer to a point contact, as shown previously, will actually be used.

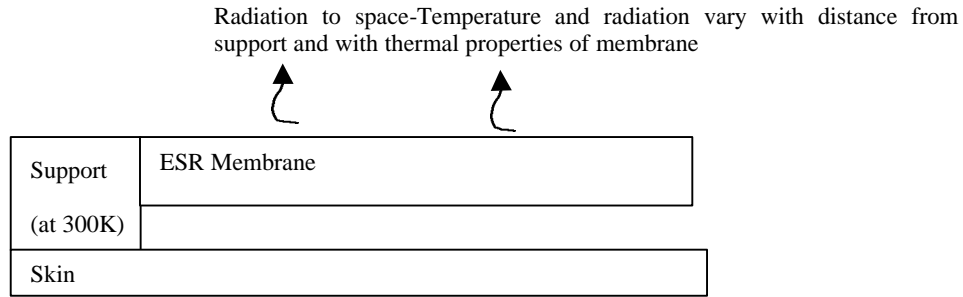


Figure 9. Structure for Thermal Modeling of ESR.

Analysis results are shown in Figure 10 for a 2 mm wide membrane, plotted as effective emissivity versus the product of the thermal conductivity and the thickness of the membrane. These results indicate the initial geometry will have about 2-4 mm spacing between supports, with a polyimide thickness below 2 micrometers.

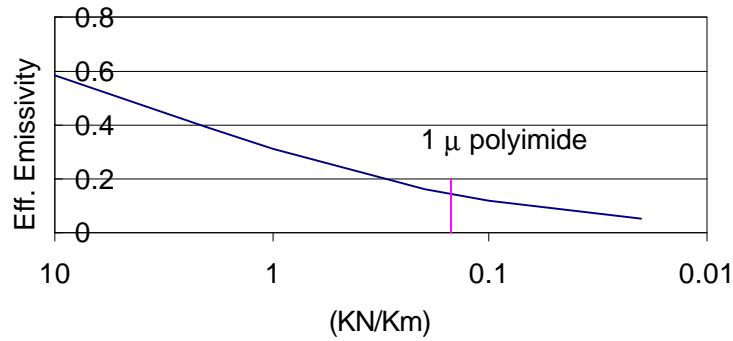


Figure 10. Emissivity versus Thermal Conductivity for 2 mm long ESR Film. Also shown is marker for 1 μ m polyimide.

Predicted Operating Voltage of MicroESR

To determine if the above structure is physically rugged, some mechanical modeling was performed using the above geometries and the elastic constants of the polyimide. For the structure design, we arbitrarily elected to select a membrane thickness that would be free standing over its width; i.e. it would not touch the skin under the force of gravity. Under these conditions, the deflection of the ESR can be modeled as a cantilever with the fixed end corresponding to the point of attachment of the film to the hinge. The length and thickness of the ESR where the end would just contact the skin with 5 micrometer spacing were then calculated.

In this model, the film is subject to a uniform gravitational force due to its mass. Since the film spacing is expected to be $\sim 5\mu\text{m}$, the length (L) of film required to obtain a maximum deflection at the free end of 5 μm was calculated, using (Nash, 1994):

$$EI y''(x) = M \quad (5)$$

where E is the modulus of elasticity (for Kapton, $E = 2.5 \times 10^9 \text{ N/m}^2$), I is the (area) moment of inertia (for a rectangular block $I = Lt^3/12$ with L the length and t the thickness (Shigley and Mitchell, 1983), M is the bending moment and y'' is the second derivative of y with respect to x. The geometry is shown below in Figure 11.

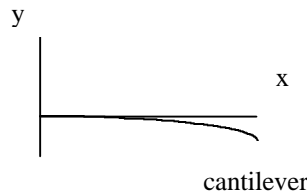


FIGURE 11. Cantilever Geometry.

For a cantilever fixed at one end subject to a uniformly distributed force, the maximum deflection is given by (Nash, 1994)

$$\Delta^* = wL^4 / 8EI \quad (6)$$

where $w = mg/L$ is the (uniform) force per unit length. Solving for a square geometry (i.e. film length = width), for a given maximum deflection Δ^* (5 μm) and thickness t, one obtains for the length

$$L = (2Et^2\Delta^* / 3\rho g)^{1/4} \quad (7)$$

Figure 12 provides results of these calculations for different film thicknesses. This calculation indicates that for film thicknesses on the order of a few microns, maximum film lengths of a fraction of a cm are possible.

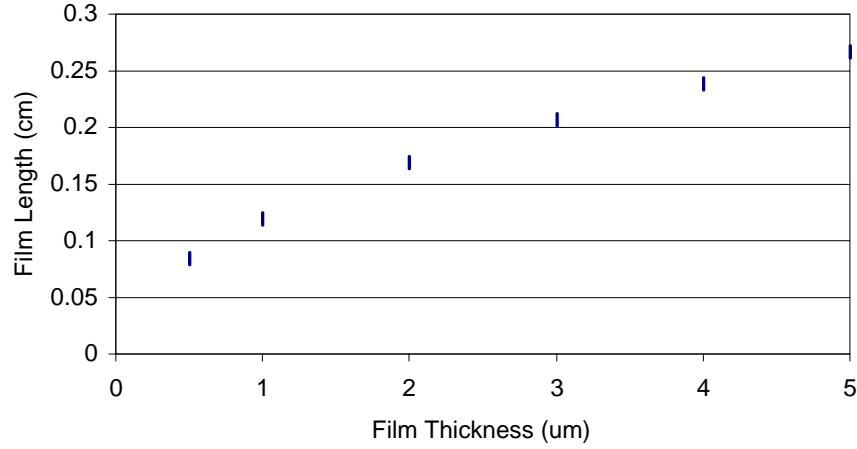


FIGURE 12. Film Length for 5 μm Deflection under Gravity.

Next, calculations were performed to estimate the DC voltage required to change the operational state of the micro-ESR. Electrically, the ESR device behaves as a high quality capacitor. The calculation is complicated by the fact that the force between the two “plates” is inversely proportional to the square of the distance between them (i.e. for the same applied voltage, a plate separation of half of the original distance results in a quadrupling of the force). As a simplification, we utilize the fact that, in the initial state, the electric field between the “plates” is uniform, and thus the force on the film (top plate) also is uniform. For a parallel plate capacitor, the electric field between the two plates is (Griffiths, 1989):

$$E = \sigma / 2\epsilon_0 \quad (8)$$

Where σ is the surface charge density ($\sigma = q/A$) and ϵ_0 is the permittivity of free space ($8.85 \times 10^{-12} \text{ C}^2/\text{Nm}^2$). The potential difference between the capacitor plates is then:

$$V = qd/\epsilon_0 A \quad (9)$$

and the electrostatic force

$$F = qE.$$

From these equations, in the initial configuration, when a potential V is applied, the force per unit length on the film initially is uniformly distributed and given by

$$w = F/L = \epsilon_0 L(V/d)^2 \quad (10)$$

where d is the initial plate separation.

To determine a first estimate of the DC voltage required to pull the film down to the base, the uniform gravitational force used in the previous calculation was replaced by the uniform electrostatic force due to the capacitive nature of the ESR. Calculations were performed to determine the voltage required to move the free end of the cantilevered micro-ESR to $1/2$ and $1/4$ of the 5 μm gap spacing. These also should be reasonable and conservative assumptions due to the increasing forces experienced with decreasing separation (i.e. once the device is deflected by this amount, the increased force will result in ensuring the film is completely attracted to and contacts the base). Figures 13 and 14

show the results obtained for movement of $\frac{1}{2}$ and $\frac{1}{4}$ of the $5\ \mu\text{m}$ gap spacing respectively. For the device sizes calculated previously, the maximum operating voltage required is a few volts (and in most instances $< 1\text{V}$).

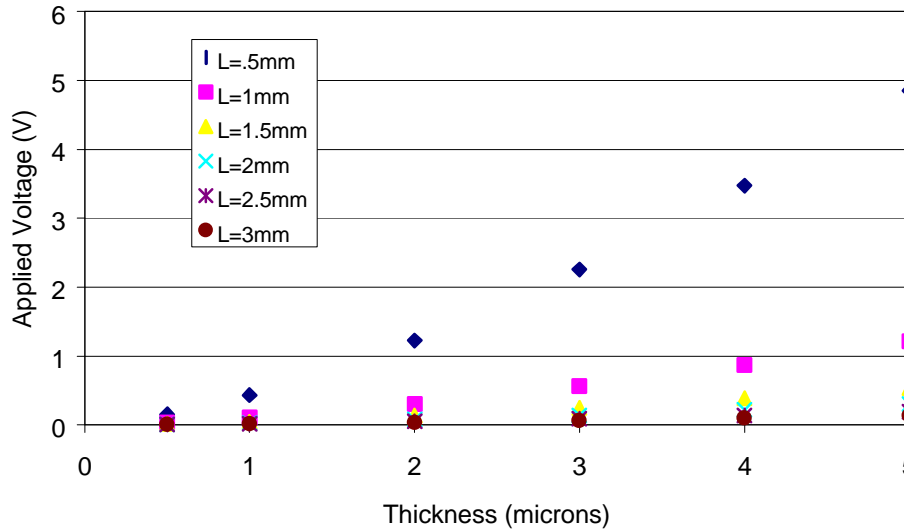


FIGURE 13. Applied Voltage Required to Deflect Free End of Micro-ESR $\frac{1}{2}$ of Gap Spacing.

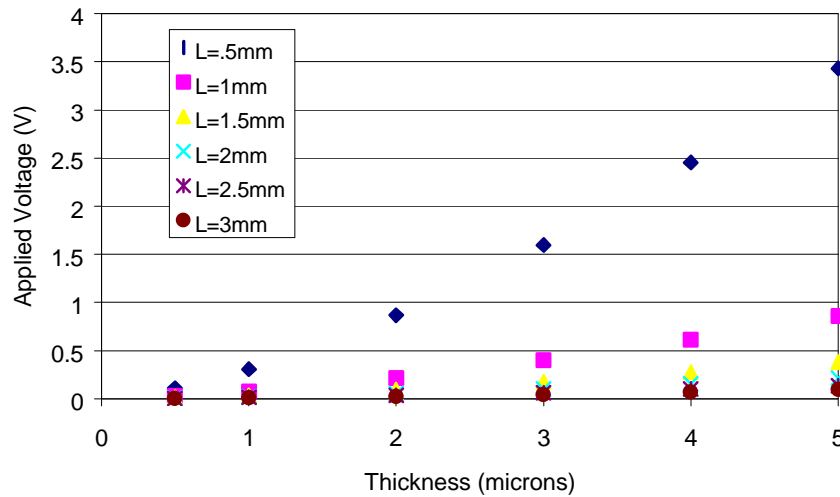


FIGURE 14. Applied Voltage Required to Deflect Free End of Micro-ESR $\frac{1}{4}$ of Gap Spacing.

CONCLUSIONS

In this paper we have described some results on an existing thermal control device which uses electrostatic hold-down of a high emissivity composite film to control spacecraft skin temperature. Results were presented on the emissivity values obtained with the existing structures. We have also described an approach which dramatically reduces the size of the structure, resulting in an appliqué which can be applied to the outer skin and still achieve high changes in the effective values of the emissivity. Calculations were presented showing the limitation on the low

emissivity values with the size and the thermal conductivity of the membrane layer, as well the calculated operating voltages.

NOMENCLATURE

A = area (m^2)
d = plate separation (m)
E = modulus of elasticity (N/m^2)
 \mathcal{E} = electrostatic field
F = number of molecules leaving surface
 \mathcal{F} = electrostatic force (N)
g = gravitational constant (9.8 m/s^2)
I = area moment of inertia (m^4)
k = Boltzmann's constant ($1.381 \times 10^{-23} \text{ J/K}$)
L = film length (m)
m = mass (kg)
M = bending moment (Nm^2)
n = molecular density (m^{-3})
q = charge (C)
Q = heat transfer density (W/m^2)
t = film thickness (m^3)
 T_{esr} = ESR temperature (K)
 T_g = gas temperature (K)
 T_{skin} = spacecraft skin temperature (K)
v = molecular speed (m/s)
V = voltage (V)
w = force per unit length (N/m)
x = length (m)
y = length (m)
 \ddot{A}^* = deflection (m)
 \mathring{a} = emissivity
 $\mathring{A}\mathring{A}$ = change in emissivity between operational states
 \mathring{a}_0 = permittivity of free space ($8.85 \times 10^{-12} \text{ C}^2/\text{Nm}^2$)
 \mathring{n} = mass density (kg/m^3)
 \mathring{o} = surface charge density (C/m^2)

ACKNOWLEDGMENTS

This work was supported by NASA Goddard Space Flight Center under Contract# NAS5-01043 and Air Force Research Laboratory under Contract #F33615-02-M-5034.

REFERENCES

- Balthazur, R., http://www.shef.ac.uk/~spare/summer_school
Chapman, S. and Cowling, T.G., *The Mathematical Theory of Non-Uniform Gases*, Cambridge University Press, Cambridge, UK, 1991, pp. 97-109
Griffiths, D. J.; *Introduction to Electrodynamics* (Second Ed.); 1989; Prentice Hall; Upper Saddle River, NJ; pp. 106-107
Nash, W. A.; *Strength of Materials* (Third Ed.); 1994; McGraw-Hill; New York, NY; pp. 197 – 202
Raif, F., *Fundamentals of Statistical and Thermal Physics*, McGraw-Hill, New York, NY, 1965, pp. 262-269
Shigley, J. E. and Mitchell, L. D.; *Mechanical Engineering Design* (Fourth Ed.); 1983; McGraw-Hill; New York, NY; p. 813